Ministry of Education and Science of Ukraine
National Aviation University

DIAGNOSTICS OF GAS PUMPING UNITS

Method Guide to Calculation and Graphic Work
for students of specialty 142 «Power Machinery»

Kyiv 2024

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The method guide contains methodical recommendations for calculation and graphic work on the academic discipline "Diagnostics of gas pumping units".

Intended for higher education seekers of specialty 142 "Power Machinery", that study in English according to the Educational Professional Program "Gas Turbine Plants and Compressor tations"

Д 44 **Діагностика газоперекачувальних агрегатів**: методичні рекомендації до виконання розрахунково графічної роботи/ уклад.: О.С.Якушенко, О.Г.Андрієць, І.І.Гвоздецький. – К.: НАУ, 2024. – 31 с.

Містять методичні рекомендації до виконання розрахунково графічної роботи з дисципліни «Діагностика газоперекачувальних агрегатів».

Для студентів спеціальності 142 "Енергетичне машинобудування", які навчаються за ОПП «Газотурбінні установки та компресорні станції» англійською мовою.

1. GENERAL INFORMATION ABOUT GAS PUMPING UNITS AND THEIR PURPOSE IN THE GAS TRANSPORTATION SUSTEM

Gas pumping units refers to the main technological equipment of compressor stations, which ensures the transportation of natural gas through the main gas pipeline, and also compresses natural gas at the compressor stations of gas pipelines and underground gas storage facilities .

The gas pumping unit (GPU) **consists of the following structural components** and **systems**:

- natural gas compressor,
- supercharger drive,
- suction and discharge devices (in the case of a gas turbine drive),
- automatic control systems,
- lubrication and cooling systems,
- fuel, air and oil communications and auxiliary equipment.

According to the type of superchargers GPUs are distinguished into:

- piston gas motor compressors (PGMC) or gas-motor compressors (GMC);
- gas pumping units with centrifugal superchargers.

According to the drive type gas pumping units are divided into:

- GPU with an internal combustion gas engine (**gas piston engines),**
- GPU with **a gas turbine engine drive,**
- GPU with **an electric drive** (that is, with a drive from an electric motor).

Gas pumping units with a gas turbine drivers, in turn, are divided into GPU with **stationary gas turbine installations** and GPU which are driven by **aviation gas turbine engines** and GPU which are driven by gas turbine engines of the **ship type**.

According to the level of the gas pressure created at the output, piston gas-motor gas engines are divided into **low-, medium- and high-**

pressure units. **Low-pressure** compressors with the outlet gas pressure ranging from 0.3 to 2 MPa are used mainly at main compressor stations for transporting gas from depleted fields and oil gas directly from oilfields. . They are also used at compressor stations for supplying low-pressure artificial combustible gases. **Medium pressure** compressors (from **2 up to 5 MPa**) work mainly at intermediate compressor stations to increase the throughput of gas pipelines. **High-pressure** units (**from 9.8 up to-12 MPa**) are installed at compressor stations for pumping gas into underground gas storage facilities.

The **efficiency factor** of modern gas moto-compressors **reaches up to 40 %.** The capacity of the most common gas pumping units, used in Ukraine is varied from 221 up to 5510 kW (abroad from 368- up to 8100 kW). Gas pumping units with a centrifugal supercharger are widely used in our country and abroad on main gas pipelines as main units. They are also used as the first stage of gas compression when pumping gas into underground gas storages.

Centrifugal superchargers are **single-stage** (partial pressure) with a compression pressure ratio of 1.23 up to 1.25 and **duple-stage** (full pressure) with a pressure ratio of 1.45-1.7. Centrifugal superchargers are characterized by much higher productivity than reciprocating compressors (12-40 million m^3 per day.).

The efficiency of simple compression cycle gas pumping units with a centrifugal compressor is up to 29%, while the efficiency of gas pumping units with a heat regenerator may be increased up to 35%. Stationary gas turbine installations or electrical motors serve as the drivers of the gas pumping units of different power. The power of GPU driven by stationary gas turbine installations is 6, 10, 16 and 25 megawatts.

Gas turbine installations, based on aviation and ship types of gas turbine engines, differ from stationary gas turbine installations in their small dimensions and weight, which makes it possible to carry out their final assembly at manufacturing plants and deliver them to compressor stations in a finished form. Gas pumping units driven by gas turbine units, developed on the basis of aircraft engines, are made in a block-container version and are often delivered to compressor stations with fire extinguishing and explosion protection systems installed in them.

Asynchronous motors with a power of 4,500 kilowatts and synchronous electric motors with a power of 4,000 to 12,500 kilowatts are used as an electric drivers in gas pumping units. The most efficient use of electrically driven gas compressor units is achieved when compressor stations are located no further than 300 km from the power transmission line.

2. APPLICATIONS OF SIMULARITY THEORY FOR SUPERCHARGERS OF GAS PUMPING UNITS

At the compressor stations (CS) of main gas pipelines the gas pumping unit includes a centrifugal pumping unit which increases the pressure of natural gas for pumping through the gas pipeline. International standards that are in force in Ukraine define that natural gas is a homogeneous gas mixture of hydrocarbons, which consists mainly of methane CH_4, but also contains ethane C_2H_6, propane C_3H_8, butane C_4H_{10}, pentane C_5H_{12} and other hydrocarbons, as well as some non-combustible gases – nitrogen N_2, carbon dioxide CO_2, etc. In addition, natural gas may contain some non-combustible components or impurities, in particular sulfur compounds, etc. In addition, natural gas may contain some non-combustible components or impurities, in particular sulfur compounds, etc. All constituent components of natural gas are in equilibrium conditions, i.e. the values of pressure P and temperature T are the same and concentrations C are evenly distributed throughout the volume.

The pressure P_0 = 101.3 kPa and temperature T_0 = 293 K are considered as standard conditions in the calculations of processes occurring in natural combustible gases.

Modern methods of calculating the flow in the flow part of vane superchargers cannot fully take into account all the peculiarities of the movement of a real three-dimensional flow of natural gas in degrees. Therefore, today there are no accurate analytical methods for calculating the working characteristics of the gas centrifugal superchargers, which is a consequence of insufficient development of the centrifugal superchargers theory [1]. The operating characteristics of centrifugal superchargers are determined, as a rule, only experimentally during their tests on special stands.

The results of such tests of a certain number of the same type of gas centrifugal superchargers are usually summarized in order to eliminate instrumental and systematic errors and are provided by the manufacturer in the form of so-called passport characteristics, which can be presented in dimensional and dimensionless parameters.

During the operation of the centrifugal gas pumping units as part of the compressor station of the main gas transport system, the operating conditions of the compressors (initial and final pressures, gas inlet temperature, chemical composition of natural gas) as well as its properties (gas constant, density, compressibility coefficient, and others) vary widely over time

. Changes of these parameters cause a change in the forms of operating characteristics. Therefore, the passport characteristics of the centrifugal pumping unites are given usually in a consolidated form. Such aggregated characteristics of the centrifugal pumping units were built for the composition of natural gas, which are recognized as standard or calculated [1].

In the practice of designers and manufacturers of centrifugal gas superchargers, the modeling method is the most often used, that is, the increase or decrease in a certain scale of the main characteristic dimensions and geometric ratios of the prototype centrifugal supercharger, the efficiency values and the shape of the characteristics are considered satisfactory and desirable for the new centrifugal gas superchargers, which are designed according to the new raw data, such as pressure, productivity and power. Such modulation is carried out by observing the laws of similarity.

Physical phenomena occurring in geometrically similar objects are called similar if the same physical quantities are in constant ratios at the corresponding points of these spaces. These ratios are called coefficients or scales of similarity. Similar operating characteristics, which have a similar shape, can only be in superchargers, the design and modes of operation of which meet the conditions of geometric, kinematic and hydraulic similarity

The conditions of geometric similarity are the equality of the angles of the working blades at the inlet and outlet of the impeller, as well as the constancy of the ratios of the characteristic geometric dimensions.

Kinematic similarity lies in the constancy of the ratio of the corresponding speeds, or in the geometric similarity of the speed triangles of geometrically similar superchargers. The hydraulic similarity of the superchargers is achieved with the same values of the dimensionless Reynolds (Re), Euler (Eu) and Strouhal (Sh) criteria in the corresponding characteristic sections:

$$Re_a = Re_b \ ; Eu_a = Eu_b \ ; Sh_a = Sh_b,$$

where the index "a" corresponds to the initial values of the corresponding criteria, and the index "b" corresponds to their final values.

Due to the fact that the adiabatic index *k* and the speed of sound, and therefore the Mach number M depend on the physics-chemical properties of gases, the use of experimental operating characteristics of the supercharger obtained during its operation with air as working body for the analysis of operation of the same supercharger with natural gas causes discrepancies, because the conditions of hydraulic similarity of air and gas superchargers are not met. For centrifugal HPA superchargers operating, as a rule, at speeds with small numbers of M less than M=0.6, and the adiabatic index changes slightly due to the relative constancy of the composition of natural gas, it can be assumed that the conditions of hydraulic similarity are always fulfilled. Therefore, compliance with the conditions of geometric and kinematic similarity [1] is of paramount importance for such centrifugal superchargers.

If the similarity criteria are calculated correctly when constructing the operating characteristics of the centrifugal supercharger and if these criteria remain unchanged, then a similar mode of operation of the gas pumping unit will be maintained.

3. GENERAL METHODICAL RECOMMENDATIONS FOR CALCULATION AND GRAPHIC WORK PERFORMING

Gas pumping units (GPU) belong to the class of complex technical objects which constructive elements operate in complex conditions (high level of thermomechanical loads, aggressive environment, etc.). These factors cause intensive degradation processes in GPU construction elements. These processes lead to deterioration of functional and strength characteristics of constructive elements, GPU units and GPU as a whole. Increasing of fuel consumption, failure and damage of GPU are consequences of these processes. But the thermodynamic parameters of the GPU are affected not only by the technical condition of its elements, but also by external conditions and the specified mode of its operation. All this leads to the need to use special methods of processing the measured parameters of the GPU work process, designed to obtain the values of the features of the aggregate, which depend only on the technical state of GPU and its components.

During the long-term operation of gas pumping units (GPUs), degradation processes occur in them, which lead not only to the deterioration of the technical condition (TS) of the main highly loaded parts, but also to a decrease in the initial thermodynamic parameters of the GPU work process, by measuring which it is possible to evaluate the change in the efficiency of the unit as a hole.

The aim of diagnostics is GPU technical state (TS) estimation with given accuracy. The result of such diagnostics is a conclusion with information about the place, kind and cause of the fault, failure or malfunction.

The process of diagnosing any technical machine involves, first of all, measurement with a certain accuracy of the parameters of the work process that takes place in this object, and further processing of the measured parameters to assess their deviation from the initial values.

When we say about gas pumping unites we mean thermodynamic parameters of pumping natural gas and first of all its input and output pressures and temperatures.

Developing diagnosing process for GPU it is necessary to take into consideration that values of operation process parameters depend not only on object's TS but on the current level of atmosphere conditions parameters and GPU operating mode. The influence of these two factors causes a change of operation parameters, which manifold exceeds the change of these parameters caused by TS change. Besides these two factors measure errors also cause a significant influence on diagnostic results. All these factors lead to the necessity of special methods of calculation of parameters depending only on object's TS.

There are several approaches to operation parameters processing. In the calculation and graphic work two block diagrams which are shown in fig.1, are used.

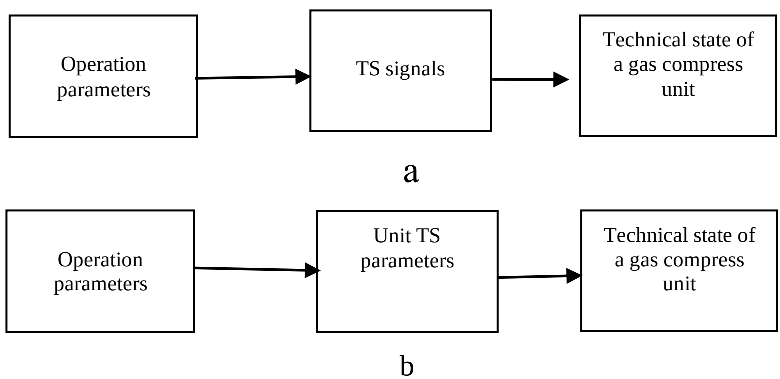

Fig.1. Diagnostic schemes

Scheme 1 a. This scheme allows to determine if engine is faultless or not. The usage of this method provides only an approximate defect localization. For the more detail defect localization all TS signs should be compared with already known “portraits” of defects, or complex criteria should be formulated. The considered algorithm requests a small amount of mathematical operations and therefore is the most common in the monitoring system of TS.

Scheme 1 b. This scheme is based on the calculation of a separate unit TS parameter, that shows the difference between the diagnosed unit TS and the etalon one. The difference in TS can be characterized by the difference of diagnosed unit operation characteristics and etalon ones. To be diagnosed by this scheme a mathematical model of the object operation and algorithm of its identification by measured parameters are used. In the home work the diagnosed unit characteristics will be estimated with the use of the direct calculation method and the mathematical model identification method.

The use of scheme 1b provides the depth of diagnosis of the unit.

Home works can be executed on the computer with any software and issued on white A4 sheets.

The example of the home work fulfilment is shown in appendix A.

Computation information for tasks 1 – 5

The variant number is appointed by the lecturer. The information for calculation is given in the form of computer files in plane text format. It consists of 100 files VarXX.dat (here and further XX is the variant number in the range 00 – 99).

These files contain the results of simulating the operation of a single-rotor gas generator. The first column of the file represents the atmospheric pressure (kPa), the second column represents the temperature at the inlet of the engine (K), the third column represents the rotor speed (%), the fourth column represents the stagnant temperature before the combustion chamber (stagnant temperature behind the compressor), the fifth column represents stagnant pressure before the combustion chamber (stagnant pressure behind the compressor) (kPa).

In the even variants the fourth column (stagnant temperature before the combustion chamber) should be processed.

In the odd variants the fifth column (stagnant pressure before the combustion chamber) should be processed.

Task 1. Primary processing of diagnostic information

The aim of primary processing of diagnostic information consists in getting diagnostic signs depending only on engine's TS and containing measure errors.

Reduction of parameters to the standard atmospheric condition

The aim of reduction is the minimization of the environment influence on diagnostic results. The theory of similarity of the GTE operation process should be used. For reduction the following relations should be used:

– reduced value of rotor frequency

$$n_{\mathrm{r}} = n \cdot \sqrt{\frac{288}{T_H^*}};$$

– reduced value of stagnant temperature in the flow path

$$T_{\mathrm{r}}^* = T^* \cdot \frac{288}{T_H^*};$$

– reduced value of stagnant pressure in the flow path

$$P_r^* = P^* \cdot \frac{101{,}325}{P_H^*},$$

where T^*_H, P^*_H – stagnant atmospheric temperature (K) and the inlet duct pressure (kPa); T^*, P^* – measured stagnant temperature (K) and pressure (kPa) in typical sections of air channel (the choice of parameter depends on the variant number); n – rotor frequency (%).

Using calculated results it is necessary to show them as a diagram:

- dependence of the pressure or temperature before the combustion chamber on the point number in the data set and on the rotor speed (2 charts placed side by side);
- dependence of the reduced diagnostic parameter (pressure or temperature) on the point number and on the reduced rotor rotational speed (2 charts placed side by side and below the corresponding previous charts).

Calculation of normalized diagnostic deviations

The TS signs are calculated as the difference between the reduced measured parameters and the standard GPU parameters.

The standard parameters are calculated by one of the following relations (depending on the variant number):

– standard dependence of reduced to SAC stagnant pressure before the combustion chamber on the reduced rotor speed

$$P_r^{*s} = a_0 + a_1\, n_r + a_2\, n_r^2 + a_3\, n_r^3 , \qquad (1)$$

where n_r – reduced rotor speed (%), **a** – vector of coefficients (table 1)

– standard dependence of reduced to SAC stagnant temperature before the combustion chamber on the reduced rotor speed

$$T_r^{*s} = b_0 + b_1\, n_r + b_2\, n_r^2 + b_3\, n_r^3 + b_4\, n_r^4 + b_5\, n_r^5 , \qquad (2)$$

where **b** – vector of coefficients (table 2)

Table 1

Coefficients of dependence (1)

a_0	a_1	a_2	a_3
8292,651	–318.212565	3.931566	–0.014667

At the next step the value of diagnostic deviation (TS sign) of the reduced parameter P_r should be calculated

$$\Delta_P = P_r - P_r^s$$

Table 2

Coefficients of dependence (2)

b_0	b_1	b_2	b_3	b_4	b_5
32497,25	–1892,8	43.93302	–0.5041968	2.8752232 10^{-3}	–6.5240737 10^{-6}

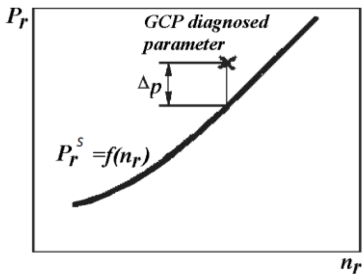

Fig. 1.Deviation of the reduced parameter from the standard one

where Δ_P is deviation of the reduced parameter from its standard value (Fig.1); P_r, P_r^s – reduced parameters values of the diagnostic GPU and standard engines (P_c^* or T_c^* – depending on the variant number).

Finally it is necessary to compare the obtained values of Δ_P with the dispersion created by the influence of measuring errors and standard model inadequacy. It is necessary to normalize diagnostic deviations Δ_P

$$\overline{\Delta_P} = \Delta_P / \Delta_{P\,norm},$$

where $\Delta_{P\,norm}$ – normalizing factor.

The value of the parameter $\Delta_{P\,norm}$ is calculated as the standard deviation by the first N = 10+*floor*(V/10) points (the function *floor*(·) returns the integer part of the quotient, V – variant number)

$$\Delta_{P\,norm} = \sqrt{\frac{\sum_{i=0}^{N-1}\left(\Delta_{P_i} - \Delta_P^{avg}\right)^2}{N-1}},$$

where Δ_P^{avg} is the average value of the N first points*

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* All relations with indices are shown in form to use in a software which numbering of elements in a vector starts from 0. In the case of a software where numbering of elements in a vector starts form 1 it is necessary to fulfill correspond alterations in these relations.

$$\Delta_P^{avg} = \frac{\sum_{i=0}^{N-1} \Delta_{P_i}}{N}$$

Using these results it is necessary to plot the dependence of the normalized diagnostic deviation on the point number.

Task 2. Preliminary diagnosing analysis and data filtration

A qualitative analysis of the time series (dependence of the unsmoothed deviation on the point number) should be made. This data should be divided into 6 segments (Fig.2).

Outlier recognition

Outlier is an error which should not appear in a properly operating gage and with proper actions of the operator. Such error must be recognized and excluded from the diagnostics process. For recognition of such errors a comparison of the sample average with the hypothetical mean of general normal population is used (variance is unknown).

Order of check:

– mark on the unsmoothed series (segment I) one point, which considerably differs from its nearest points (Fig.2 and Fig.3);

– on the right and on the left from this point mark L points (Fig. 3). Take $L=(5+floor(V/30))$. In this way the sample includes 2 L+1 points together with the checked point;

– by all 2 L points of the sample (without the checked point) calculate the sample average $M_{\overline{\Delta_P}}$ and the standard deviation $S_{\overline{\Delta_P}}$.

– find the statistic

$$T = \frac{(\overline{\Delta_P}^C - M_{\overline{\Delta P}})\sqrt{2L}}{S_{\overline{\Delta_P}}}$$

where $\overline{\Delta_P}^C$ is the checked value; T is the Student's parameter;

– as null hypothesis we take that the outlier is absent: H_0: $M_{\overline{\Delta_P}} = \overline{\Delta_P}^C$ and the alternative one: H_1: $M_{\overline{\Delta_P}} \neq \overline{\Delta_P}^C$. Find the left T^L_{cr} and right T^R_{cr} critical points knowing the level of significance α (it depends on the variant number) and the freedom degree $k = 2L - 1$. For the critical points finding Student's distribution should be used. Take α as

$$\alpha = \begin{cases} 0{,}01, & \mathrm{m} = 0, \\ 0{,}02, & \mathrm{m} = 1, \\ 0{,}1, & \mathrm{m} = 2, \\ 0{,}05, & \mathrm{m} = 3. \end{cases} \qquad m = \mathrm{mod}(V, 4)$$

where *mod*(x,y) is a function which calculates the remainder of *x/y*. The finding of critical values in this and next subchapters should be done with the tables shown in [3] or with the statistical functions of the software. If Mathcad software is used values T^L_{cr} та T^R_{cr} should be found as

$$T^L_{\mathrm{cr}} = qt(\alpha/2, k)\ ,\ T^R_{\mathrm{cr}} = qt(1\text{-}\alpha/2, k).$$

If the condition $T^L_{\mathrm{cr}} < T < T^R_{\mathrm{cr}}$ is not satisfied the checked point is an outlier;

– make a conclusion about the outlier presence/absence and its possible cause.

Task 3. Check for dispersion jump

The increase of diagnostic deviations series dispersion can be caused by a malfunction of the measuring system: partial failure of sensor, bad electrical contact in connections and so on. Besides this, such sort of defects can be caused by a malfunction of the automatic control system.

To do it the comparison of dispersions of the first and the second segments is to be fulfilled (Fig.2).

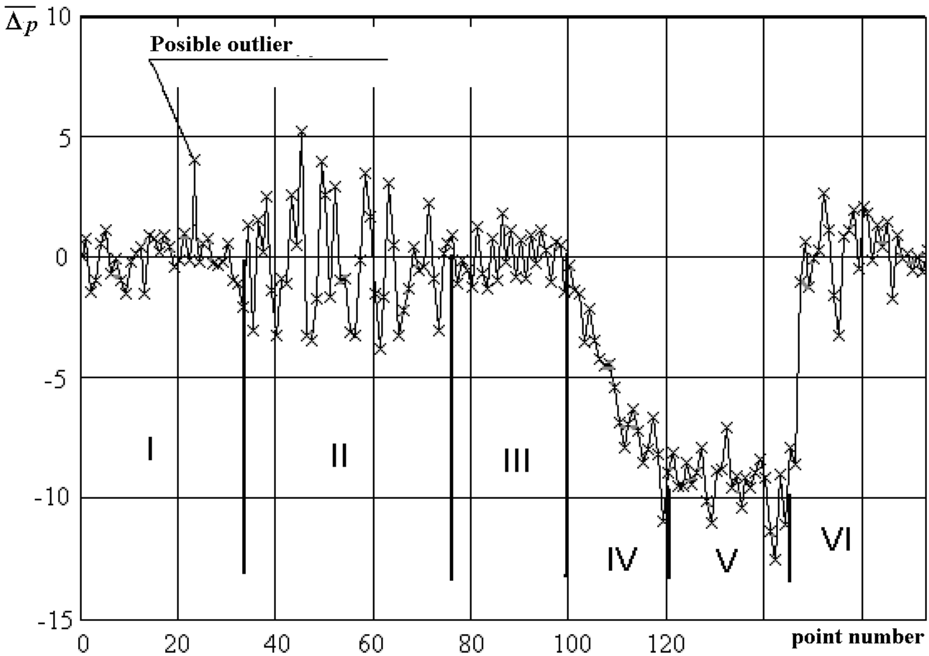

Fig.2. Division of the time series: I – horizontal segment with normal dispersion; II – horizontal segment with increased dispersion; III – horizontal segment with normal dispersion; IV – segment with gradual change of TS; V – horizontal segment of changed TS; VI – normal horizontal segment

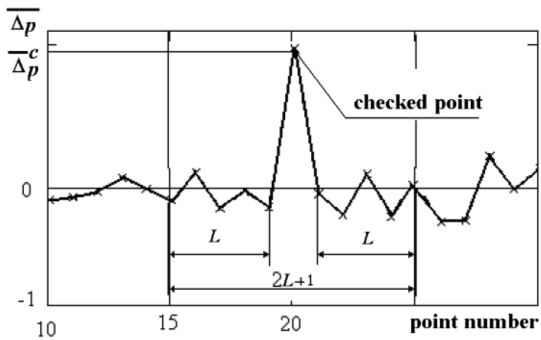

Fig.3. Outlier checking (L=5)

Check order:

– mark on the unsmoothed series L points on the right from the second segment start and on the left from the last point of the first segment (Fig.4). Take $L = 5 + floor(V/30)$;

– separately for the each group of L points calculate dispersions ;

$$S_{\overline{\Delta P}}^{I\ 2} \text{ and } S_{\overline{\Delta P}}^{II\ 2}$$

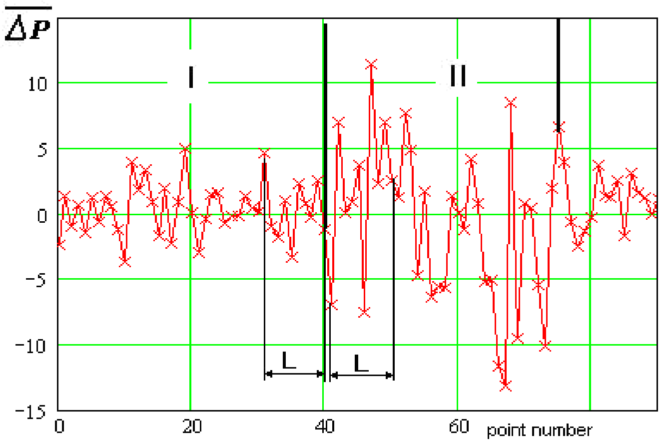

Fig. 4. Dispersion jump presence checking (L=10)

– find Fisher's statistics

$$F = \frac{S_{\overline{\Delta P}}^{II\ 2}}{S_{\overline{\Delta P}}^{I\ 2}}$$

– as the null hypothesis take the hypothesis that the dispersion jump is absent: H_0: $S_{\overline{\Delta P}}^{I} = S_{\overline{\Delta P}}^{II}$ and the alternative one: H_1: $S_{\overline{\Delta P}}^{II} > S_{\overline{\Delta P}}^{I}$. Find the critical point F_{cr} knowing the significance level of α and freedom degrees $k_1 = k_2 = L - 1$. For the determination of the critical point the Fisher's distribution should be used. Take α as

$$\alpha = \begin{cases} 0{,}05, & V - \text{even variant} \\ 0{,}02, & V - \text{odd variant} \end{cases}$$

If Mathcad software is used F_{cr} the value is found as

$$F_{cr} = qF(1\text{-}\alpha, k_1, k_2).$$

If the condition $F > F_{cr}$ is satisfied the dispersion jump is significant;

–make conclusions about the presence/absence of a dispersion jump between the first and second segments and its possible cause.

Task 4. Checking diagnostics deviation series for a trend presence

A gradual change of diagnostics deviation can be caused by gradual degradation processes which take place in GPU units: abrasive wear of compressor blades; high temperature corrosion; sealing wearing etc.

To detect a trend the correlation coefficient should be calculated and analysed. If its value considerably differs from 0 then the trend is present.

The trend searching is executed for the fourth segment (Fig.2). Every point belonging to this segment is taken into account. As the time parameter the numbers of points should be used.

Check order:

– by all diagnostic deviations that belong to the fourth segment of the series calculate the average $M^{IV}_{\overline{\Delta}_P}$ and standard deviation $S^{IV}_{\overline{\Delta}_P}$;

– by all points numbers that belong to the fourth segment calculate the average $M^{IV}_{\bar{t}}$ and standard deviation S^{IV}_{t};

– calculate the correlation coefficient

$$\rho = \frac{\mu_{t\Delta p}}{S^{IV}_{\overline{\Delta}_P}\, S^{IV}_{t}}$$

where $\mu_{t\Delta p} = \dfrac{\sum_{i=N^{III}+1}^{N^{IV}-1} (i - M^{IV}_{\bar{t}})(\overline{\Delta}_{P\,i} - M^{IV}_{\overline{\Delta}_P})}{N-1}$ - covariance moment, N – quantity of points in the fourth segment;

– find statistics

$$T = \rho \frac{\sqrt{N-2}}{\sqrt{1-\rho^2}}$$

where T is the Student’s statistic;

–as the null hypothesis take the hypothesis that the trend is absence: H_0: $\rho = 0$. Alternative hypotheses H_1: $\rho \neq 0$. Find critical points T^L_{cr} and T^R_{cr} with significance level α and freedom degree $k = N - 2$. Take α as

$$\alpha = \begin{cases} 0{,}01, & m = 0, \\ 0{,}02, & m = 1, \\ 0{,}1, & m = 2, \\ 0{,}05, & m = 3. \end{cases} \qquad m = \mathrm{mod}(V, 4)$$

If Mathcad software is used the values T^L_{cr} та T^R_{cr} should be found as

$$T^L_{\mathrm{cr}} = qt(\alpha/2, k)\ ,\ T^R_{\mathrm{cr}} = qt(1\text{-}\alpha/2, k).$$

If the condition $T^L_{\mathrm{cr}} < T < T^R_{\mathrm{cr}}$ is not satisfied the series trend is present;

– make a conclusion about the presence (absence) of a trend on the fourth segment and its possible cause.

Task 5. Check diagnostics deviation for jump presence

A stepwise change of diagnostic deviation can be caused by the manifestation of a sudden defect such as e.g. spring destroying in an automatic control system, break of blades, sensor fault ets.

Check order:

– mark on the unsmoothed series L points on the right from the sixth segment start and on the left from the last point of the fifth segment (Fig.2, Fig.5). Take $L = 4 + floor(V/24)$;

– separately for each group of L points calculate average values $M^V_{\Delta_P}$ and $M^{VI}_{\Delta_P}$ and standard deviations $S^V_{\Delta_P}$ and $S^{VI}_{\Delta_P}$;

– find the Student's statistics

$$T = \frac{\left(M^{VI}_{\Delta_P} - M^V_{\Delta_P}\right)\sqrt{L}}{\sqrt{{S^{VI}_{\Delta_P}}^2 + {S^V_{\Delta_P}}^2}};$$

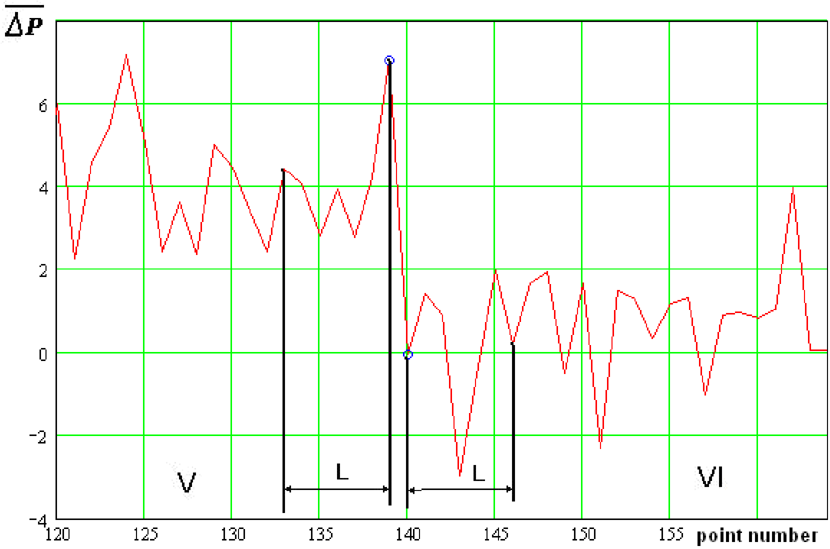

Fig.5. Mean jump check (L = 6)

– as the null hypothesis take the hypothesis that the jump is absent: H_0: $M^{V}_{\overline{\Delta P}} = M^{VI}_{\overline{\Delta P}}$. Alternative hypotheses H_1: $M^{V}_{\overline{\Delta P}} \neq M^{VI}_{\overline{\Delta P}}$. Find the critical points T^{L}_{cr} and T^{R}_{cr} with significance level α and freedom degree $k = 2(L-1)$. Take α as

$$\alpha = \begin{cases} 0.001, & m = 0 \\ 0.005, & m = 1 \quad m = \text{mod}(V, 3) \\ 0.01, & m = 2 \end{cases}$$

If Mathcad software is used the values T^{L}_{cr} та T^{R}_{cr} should be found as

$$T^{L}_{cr} = qt(\alpha/2, k)\ ,\ T^{R}_{cr} = qt(1-\alpha/2, k).$$

If the condition $T^{L}_{cr} < T < T^{R}_{cr}$ is not satisfied the jump is present;

– make a conclusion about the presence (absence) of the jump.

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Appendix A

EXAMPLE OF CALCULATION AND GRAPHIC WORK FULFILMENT

MINISTRY OF EDUCATION AND SCIENCE

NATIONAL AVIATION UNIVERSITY

AEROSPACE FACULTY

DEPARTMENT OF AVIATION ENGINES

Calculation and Graphic Work
on discipline
DIAGNOSTICS OF GAS PUMPING UNITS

VARIANT ____

Performed by student of the ___ group

____

Accepted by ________________________

Kyiv – 20___

Data loading and dividing

$m := READPRN("var0000.txt")$

$$i := 0 .. rows(m) - 1$$

$Pvx := m^{\langle 0 \rangle}$ $Tvx := m^{\langle 1 \rangle}$ $n := m^{\langle 2 \rangle}$

$Tk := m^{\langle 3 \rangle}$ $Pk := m^{\langle 4 \rangle}$

$Pvx_i =$

	0
0	71.69
1	97.27
2	72.44
3	94.91
4	70.01
5	76.29
6	...

$Tvx_i =$

	0
0	296.7
1	277
2	308.2
3	272.3
4	301.1
5	279.7
6	...

$n_i =$

	0
0	85.82
1	86.4
2	86.08
3	86.63
4	87.27
5	86.78
6	...

$Tk_i =$

	0
0	537.6
1	526.2
2	547.7
3	526.8
4	549.3
5	533.9
6	...

$Pk_i =$

	0
0	439.6
1	718.6
2	420.9
3	726.7
4	450
5	559.2
6	...

Task 1. Primary processing of diagnostic information

The aim of reduction is the minimization of environment influence on diagnostic results. The theory of similarity of GTE operation process should be used. For reduction next relations should be used:

– reduced value of rotor frequency

$$nzv_i := n_i \cdot \sqrt{\frac{288}{Tvx_i}}$$

– reduced value of stagnant temperature in flow path

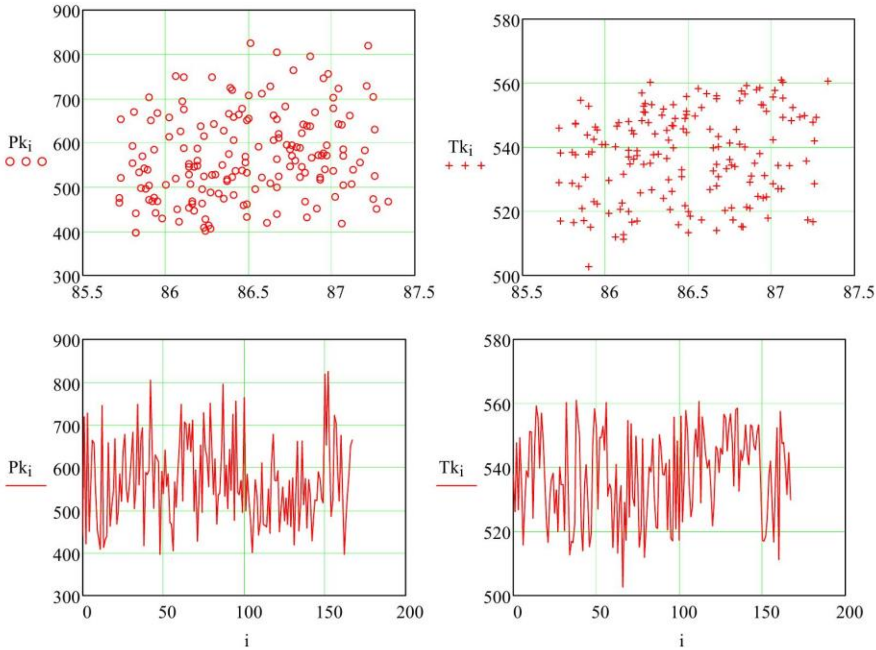
$$Tkzv_i := Tk_i \cdot \frac{288}{Tvx_i}$$

– reduced value of stagnant pressure in flow path

$$Pkzv_i := Pk_i \cdot \frac{101.325}{Pvx_i}$$

Using calculated results it is necessary to show as a diagram:

- dependence of the pressure or temperature before combustion chamber on point number in data set and on rotor speed (2 charts placed side by side);
- dependence of reduced diagnostic parameter (the pressure or temperature) on point number and on reduced rotor rotational speed (2 charts placed side by side and below the corresponding previous charts).

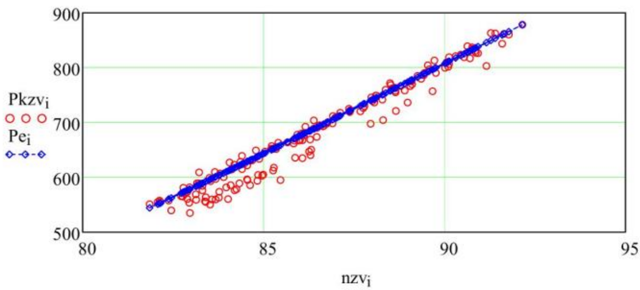


TS signs are calculated as difference between reduced measured parameters and standard GPU parameters.
Standard parameters are calculated by one of the next relations (depending on the variant number):
– standard dependence of reduced to SAC stagnant pressure before combustion chamber on reduced rotor speed

$a_0 := 8292.651 \quad a_1 := -318.212565 \quad a_2 := 3.931566 \quad a_3 := -0.014667$

$$Pe_i := a_0 + a_1 \cdot nzv_i + a_2 \cdot (nzv_i)^2 + a_3 \cdot (nzv_i)^3$$

where nr – reduced rotor speed (%), a – vector of coefficients



At the next step the value of diagnostic deviation (TS sign) of reduced parameter Pr should be calculated

$$dp_i := Pkzv_i - Pe_i$$

Finally it is necessary to compare obtained values of with dispersion created by influence of measuring errors and standard model inadequacy. It is necessary to normalize diagnostic deviations by N first points

$N := 11$

Mean value

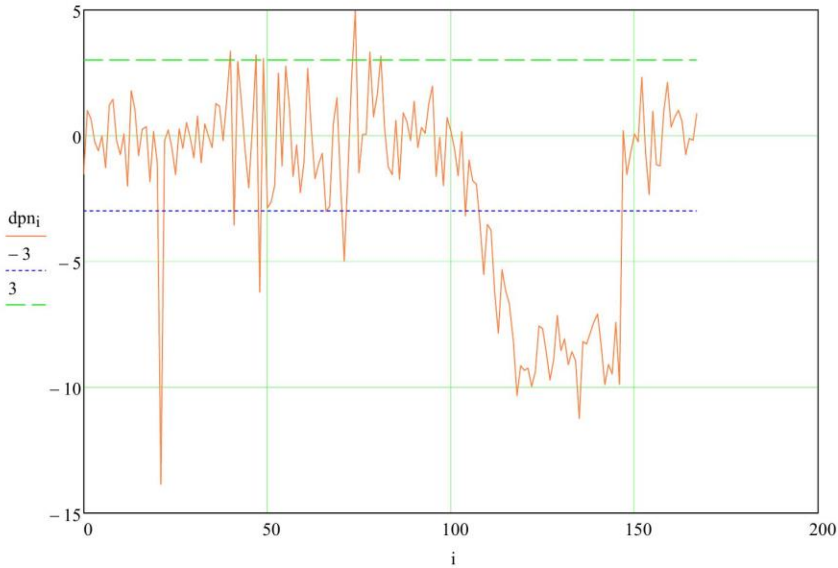
$$mbp := \sum_{i=0}^{N-1} \frac{dp_i}{N} = -0.182$$

Standard deviation

$$sbp := \sqrt{\sum_{i=0}^{N-1} \frac{(dp_i - mbp)^2}{N-1}} = 4.551$$

Diagnostic deviations normalization

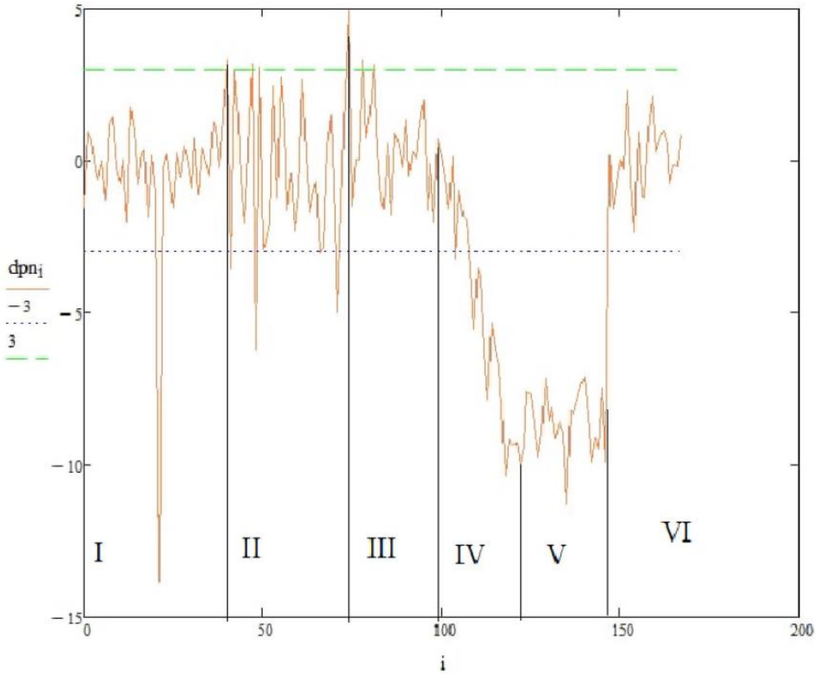
$$dpn_i := \frac{dp_i}{sbp}$$



Task 2. Preliminary diagnosing analysis and data filtration

Qualitative analysis of time series (dependence of unsmoothed deviation on point number) should be made. This data should be divided into 6 segments

Division of the time series: I – horizontal segment with normal dispersion; II – horizontal segment with increased dispersion; III – horizontal segment with normal dispersion; IV – segment with gradual change of TS; V – horizontal segment of changed TS; VI – normal horizontal segment



Outlier recognition

Outlier is an error which should not appear in properly operating gage and with proper actions of operator. Such error must be recognized and excluded from diagnostics process. For recognition of such errors comparison of sample average with hypothetical mean of general normal population is used (variance is unknown).

Order of check:

– mark on unsmoothed series (segment I) one point, which considerably differs from its nearest points t1ta0t0nt0te1 on the right and on the left from this point mark L points (Fig. 3). Take L In this way the sample includes $2L+1$ points together with checked point;

$$L := 5 \qquad \alpha := 0.02$$

Extracted data for analize

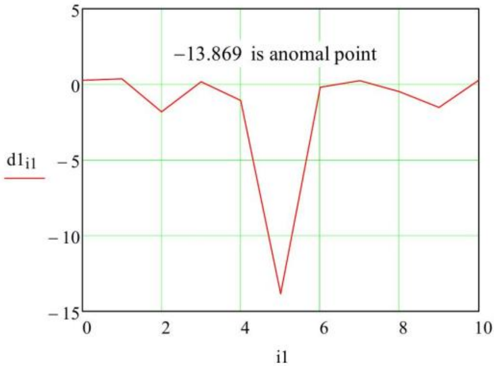
$i1 := 0..2L \qquad i11 := 0..2L-1$

$d1_{i1} :=$

0.245
0.352
−1.835
0.162
−1.074
−13.869
−0.203
0.216
−0.493
−1.554
0.256

$d11_{i11} :=$

0.245
0.352
−1.835
0.162
−1.074
−0.203
0.216
−0.493
−1.554
0.256



Mean value

$$M1 := \frac{\sum_{i11} d11_{i11}}{L} = -0.786$$

Standard deviation

$$S1 := \sqrt{\frac{\sum_{i11} \left(d11_{i11} - M1\right)^2}{2L - 1}} = 0.915$$

Statistic of Student

$$T := \frac{(-13.869 - M1)\cdot\sqrt{2\cdot L}}{S1} = -45.195$$

Critical point

$$k := 2\cdot L - 1 = 9$$

$$Tk := qt\left(1 - \frac{\alpha}{2}, k\right) = 2.821$$

Conclusion |T|>>Tk => The point is abnomal one

Task 3. Check for dispersion jump

Increase of diagnostic deviations series dispersion can be caused by malfunction of measuring system: partial failure of sensor, bad electrical contact in connections and so on. Besides this, such sort of defects can be caused by malfunction of automatic control system.
To do it comparison of dispersions of the first and the second segments is to be fulfilled.
Check order:
– mark on unsmoothed series L points on the right from the second segment start and on the left from the last point of the first segment.

$$L_2 := 5$$

Data

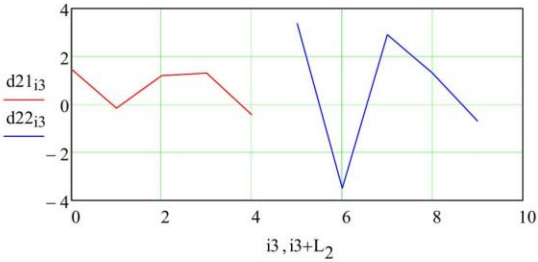
$$i3 := 0 .. L_2 - 1$$

$d21_{i3} :=$

1.471
−0.167
1.2
1.3
−0.429

$d22_{i3} :=$

3.371
−3.5
2.9
1.3
−0.7



Mean values

$$M21 := \frac{\sum_{i3} d21_{i3}}{L_2} = 0.675 \qquad M22 := \frac{\sum_{i3} d22_{i3}}{L_2} = 0.674$$

Standard deviations

$$S21 := \sqrt{\frac{\sum_{i3} \left(d21_{i3} - M21\right)^2}{L_2 - 1}} = 0.898$$

$$S22 := \sqrt{\frac{\sum_{i3} \left(d22_{i3} - M22\right)^2}{L_2 - 1}} = 2.825$$

Fishers's statistica

$$F := \frac{S22^2}{S21^2} = 9.893$$

Critical point

$$k_2 := L_2 - 1$$

$$Fkr := qF\left(1 - 0.1, k_2, k_2\right) = 4.107$$

$$F > Fkr = 1$$

Conclusion: the jump of variance is significant. Possible causes are malfunctions in the system for measuring the parameters of operation, namely: partial malfunction of the sensor, poor electrical contact in the plug connections, or malfunction of the automatic control system.

Task 4. Checking diagnostics deviation series for trend presence

Gradual change of diagnostics deviation can be caused by gradual degradation processes which take place in GPU units: abrasive wear of compressor blades; high temperature corrosion; sealing wearing etc.

Length of the checked part

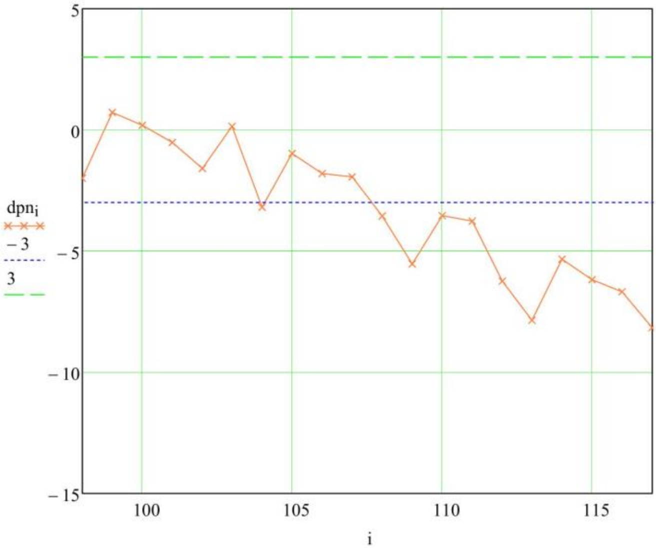
$L_4 := 19$

Checked data

$i4 := 0 .. L_4 - 1$

$d4_{i4} :=$

0.30
0.25
−0.6
−1.63
0.24
−3
−1
−1.7
−1.72
−3.55
−5.45
−3.55
−3.70
−6.3
−7.9
−5.4
−6.2
−6.7
−8.1



Correlation coefficient

Parameter of time

$t_{i4} := i4$

Mean values

$$M4 := \frac{\sum_{i4} d4_{i4}}{L_4} = -3.458 \qquad M4t := \frac{\sum_{i4} t_{i4}}{L_4} = 9$$

Standatd deviations

$$S4 := \sqrt{\frac{\sum_{i4} \left(d4_{i4} - M4\right)^2}{L_4 - 1}} = 2.795 \qquad S4t := \sqrt{\frac{\sum_{i4} \left(t_{i4} - M4t\right)^2}{L_4 - 1}} = 5.627$$

Covariance moment

$$Mu := \frac{\left[\sum_{i4}\left[(t_{i4} - M4t)\cdot(d4_{i4} - M4)\right]\right]}{L_4 - 1} = -14.581$$

Correlation coefficient

$$Ro := \frac{Mu}{S4t \cdot S4} = -0.927$$

Statistc of Student

$$T_2 := Ro \cdot \frac{\sqrt{L_4 - 2}}{\sqrt{1 - Ro^2}} = -10.192$$

Critical point

$$k := L_4 - 2 \qquad alfa := 0.05$$

$$Tkr := qt\left(1 - \frac{alfa}{2}, k\right) = 2.11$$

$$T_2 := 10.192$$

$$T_2 > Tkr = 1$$

Conclusion: Given that T is greater than Tkr, the trend of the parameters is statistically significant. Possible causes: bearing wear, abrasive wear of blades or their contamination

Task 5. Check diagnostics deviation for jump presence

Stepwise change of diagnostic deviation can be caused by the manifestation of a sudden defect such as e.g. spring destroying in an automatic control system, break of blades, sensor fault ets.

– mark on unsmoothed series L points on the right from the sixth segment start and on the left from the last point of the fifth segment

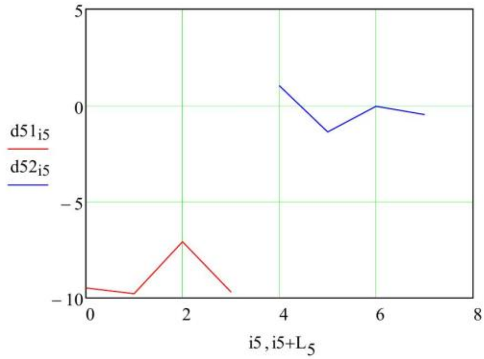
$$L_5 := 4$$

Checked data

$$i5 := 0 .. L_5 - 1$$

$d51_{i5} :=$ $d52_{i5} :=$

d51	d52
−9.5	1
−9.8	−1.4
−7.1	−0.06
−9.7	−0.5



Mean values

$$M51 := \frac{\sum_{i5} d51_{i5}}{L_5} = -9.025 \qquad M52 := \frac{\sum_{i5} d52_{i5}}{L_5} = -0.24$$

Standatd deviation

$$S51 := \sqrt{\frac{\sum_{i5} \left(d51_{i5} - M51\right)^2}{L_5 - 1}} = 1.289$$

$$S52 := \sqrt{\frac{\sum_{i5} \left(d52_{i5} - M52\right)^2}{L_5 - 1}} = 0.997$$

Statistic of Student

$$T_3 := \frac{(M52 - M51)\cdot\sqrt{L_5}}{\left[\sqrt{(S51)^2 + S52^2}\right]} = 10.779$$

Critical point

$k_5 := 6$ $\alpha_5 := 0.01$

$$Tkr_3 := qt\left(1 - \frac{\alpha_5}{2}, k_5\right) = 3.707$$

$T_3 > Tkr_3 = 1$

Conclusion: Given that T is greater than Tkr, the trend of the parameters is statistically significant. Possible causes: destruction of the spring in the automatic control system, breakage of the blade, failure of the sensor.